Kaon Structure at JLab Hall C

Richard Trotta

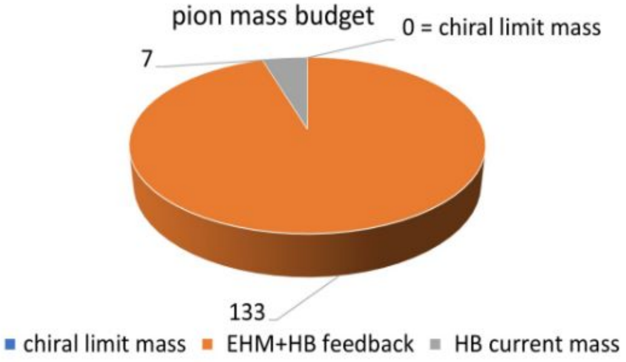
and the KaonLT collaboration

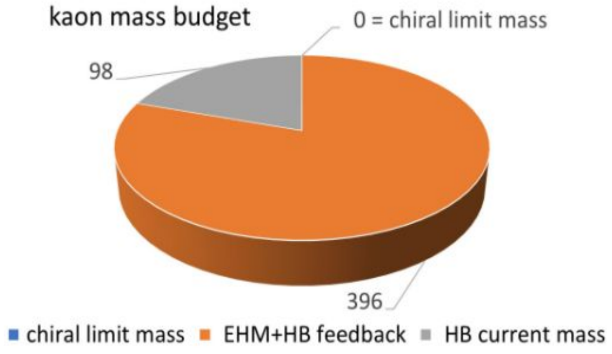
Overview of Meson Structure

- The pion is both the lightest bound quark system with a valence $\bar{q}q$ structure and a Nambu-Goldstone boson

- There are exact statements from QCD in terms of current quark masses due to PCAC
[Phys. Rep. 87 (1982) 77; Phys. Rev. C 56 (1997) 3369; Phys. Lett. B420 (1998) 267]
  - From this, it follows the mass of bound states increase as $\sqrt{m}$ with the mass of the constituents
  - In both DSE and lQCD, the mass function of quarks is the same, regardless of what hadron the quarks reside in. It is the DCSB that makes the pion and kaon masses light.

- Pseudoscalar masses are generated dynamically

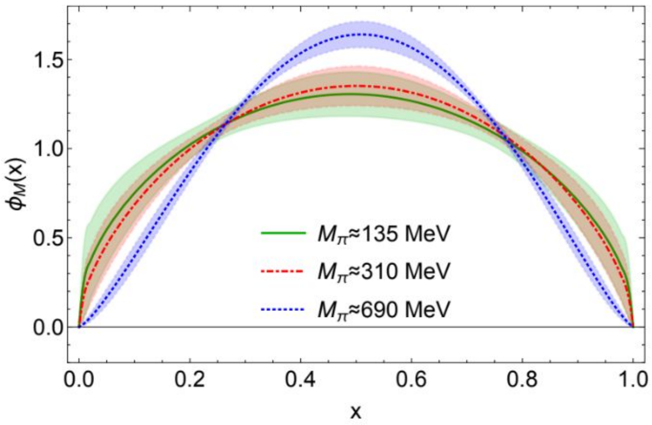




Journal of Physics G (2021) arXiv:2102.11788

Kaon Structure

- Data suggests that heavier flavor quark mass is primarily generated through the Higgs mechanism
- The kaon sits in a unique position because its quark composition is both light and heavy
  - The kaon consists of an up quark and a strange antiquark
  - A competition seems to arise between DCSB and the Higgs mechanism
- The kaon is also a pseudo Nambu-Goldstone boson which makes it a prime candidate for deeper DCSB studies

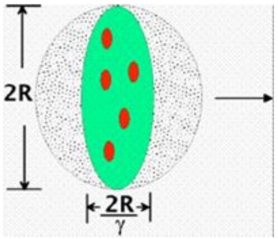


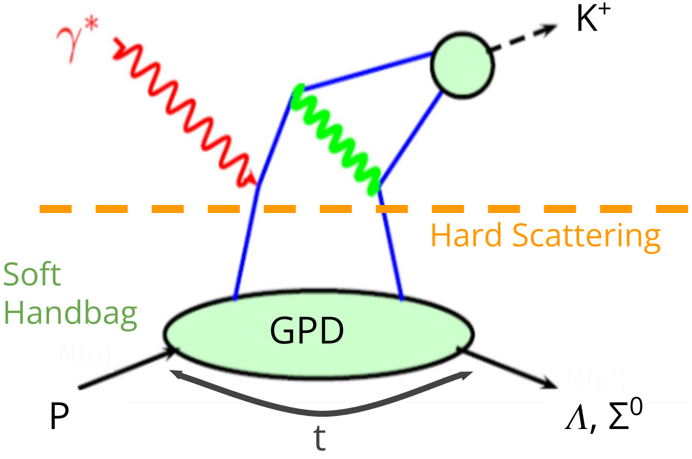
M_π~140 MeV
M_K~494 MeV

Journal of Physics G (2021) arXiv:2102.11788

Hard-Soft Factorization

- Hard-soft factorization is prerequisite for three-dimensional hadron structure studies
- This can be tested experimentally by measuring the L-T separated cross sections
- The K^+ electroproduction cross section has a Q^2 dependence at fixed x and -t
  - Provides important insight into hard-soft factorization for systems including strangeness
  - Factorization of σ_L scales to leading order Q^{-6}
  - In that regime expect σ_T to go as Q^{-8} and consequently $\sigma_L >> \sigma_T$
  - Important because partons are "frozen" transversely in the reference frame of pQCD (i.e. infinite momentum frame)

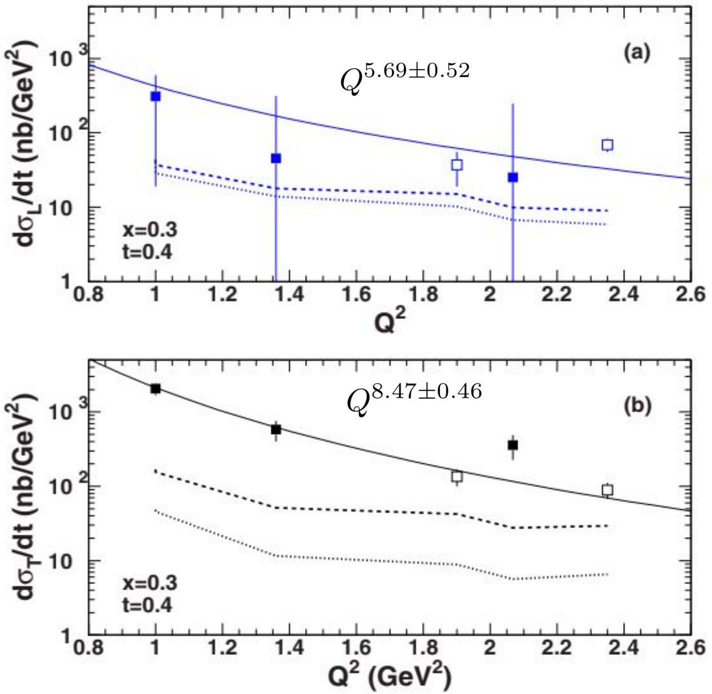




L-T Separated K^+ Data for Verifying Reaction Mechanism

- Jlab 6 GeV K^+ data demonstrated the technique of measuring the Q^2 dependence of L-T separated cross sections at fixed x/t to test QCD Factorization
  - Consistent with expected scaling of σ_L to leading order Q^{-6} but with relatively large uncertainties
- Separated cross sections over a large range in Q^2 are essential for:
  - Testing hard-soft factorization and understanding dynamical effects in both Q^2 and –t kinematics
  - Interpreting non-perturbative QCD contributions in experimentally accessible kinematics
- Hall C at JLab 12 GeV provides the facilities for such measurements

Results from JLab 6 GeV data



M. Carmignotto et al., PhysRevC ***97****(2018)025204*

Meson Form Factors

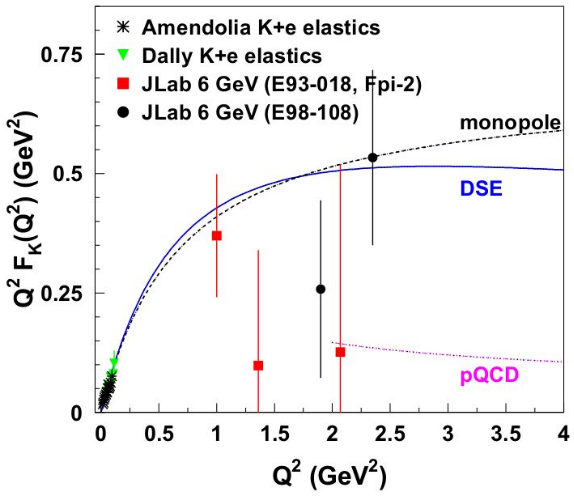
- Pion and kaon form factors are of special interest in hadron structure studies
    - Pion - lightest QCD quark system and crucial in understanding dynamic generation of mass
    - Kaon - next simplest system containing strangenes and also crucial in understanding dynamic generation of mass

- Clearest case for studying transition from non-perturbative to perturbative regions

- Jlab 6 GeV data showed the Kaon FF differs from hard QCD calculation
    - Evaluated with asymptotic valence-quark Distribution Amplitude (DA), but large uncertainties

- 12 GeV Kaon FF extraction data require:
    - measurements over a range of -t, which allow for interpretation of kaon pole contribution

Results from JLab 6 GeV data



*M. Carmignotto et al., PhysRevC **97**(2018)025204*
F. Gao et al., Phys. Rev. D 96 (2017) no. 3, 034024

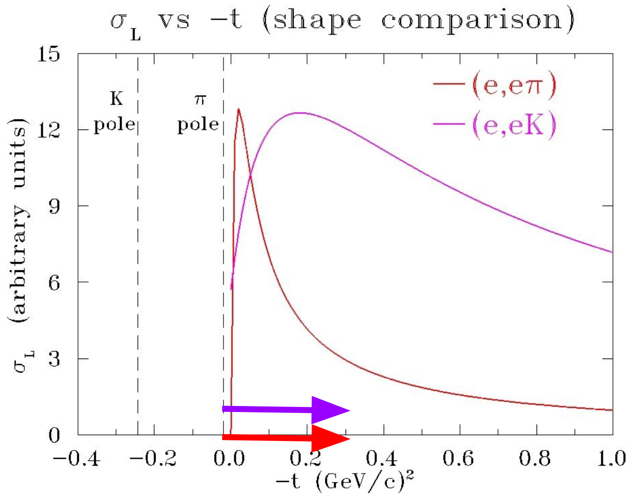
Experimental Considerations: Comparing π^+ and K^+ Form Factor

- At large -t, pion data lies a similar distance from the pole as kaon data
  - The Born term model should be approximately valid for kaon form factor
- The hard scattering limit in pQCD predicts a similar result

$$\frac{F_K(Q^2)}{F_\pi(Q^2)} \xrightarrow[Q^2\to\infty]{} \frac{f_K^2}{f_\pi^2}$$

- Requirements:
  - Full L/T separation of the cross section – isolation of σ_L (which requires $\sigma_L >> \sigma_T$)
  - Selection of the pion pole process
  - Extraction of the form factor using a model
  - Validation of the technique - model dependent checks

$$\sigma_L \approx \frac{-tQ^2}{(t-m_K^2)^2} g_{KNN}^2(t) F_K^2(Q^2,t)$$



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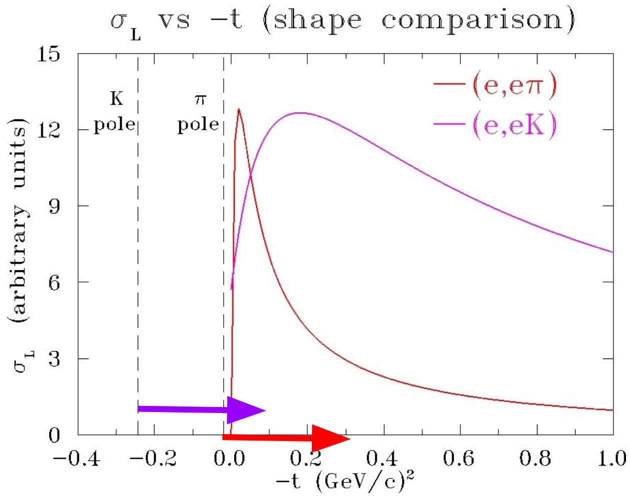
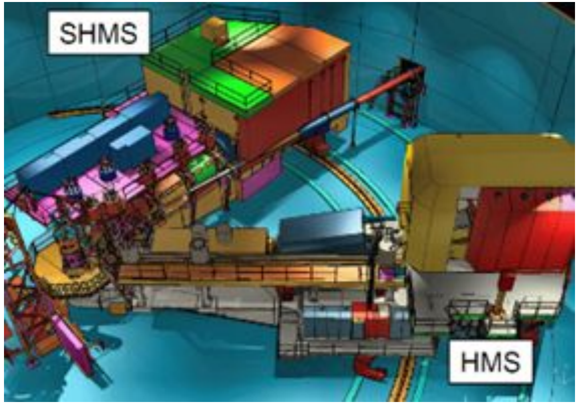


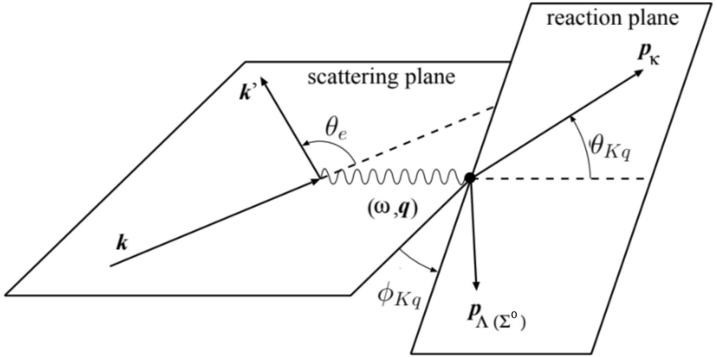
- Hall C magnetic spectrometers can provide the facilities for this measurement

Review E12-09-011 (KaonLT) Goals

- Q^2 dependence will allow studying the scaling behavior of the separated cross sections
  - First cross section data for Q^2 scaling tests (x=0.25, 0.4) with kaons
  - Highest Q^2 (Q^2=5.5 GeV^2) for L-T separated kaon electroproduction cross section
  - First separated kaon cross section measurement above W=2.2 GeV
- $p(e,e'K^+)\Lambda,\Sigma^0$ t-dependence allows for detailed studies of the reaction mechanism
  - Contributes to understanding of the non-pole QCD contributions, which should reduce the model dependence
  - Bonus: if warranted by data, extract the kaon form factor from Λ data

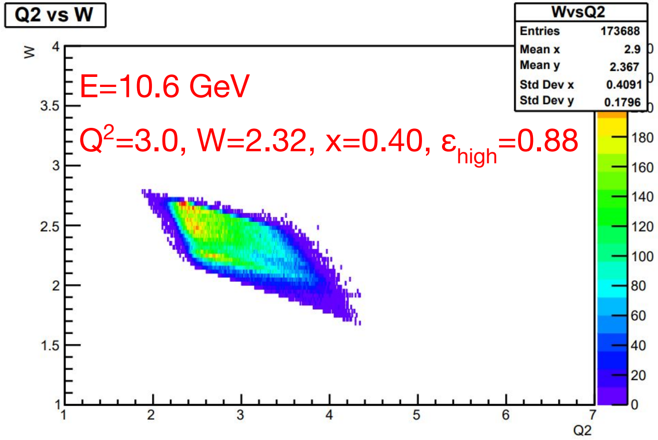
Overview Hall C at 12 GeV





KaonLT - Data Collected

- The $p(e, e'K^{+})\Lambda,\Sigma^{0}$ experiment ran in Hall C at Jefferson Lab over the fall 2018 and spring 2019.

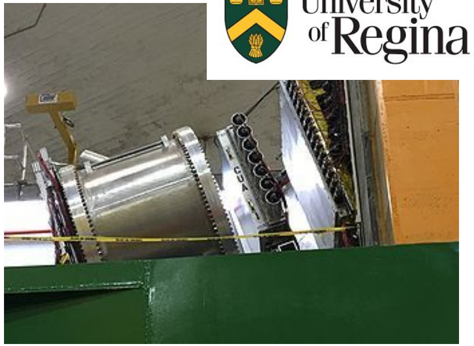


E (GeV)	Q^2 (GeV^2)	W (GeV)	x	$\epsilon_{high}/\epsilon_{low}$	$\Delta\epsilon$	Study Type
10.6/8.2	5.5	3.02	0.40	0.53/0.18	0.35	scaling
10.6/8.2	4.4	2.74	0.40	0.72/0.48	0.24	scaling
10.6/6.2	3.0	2.32	0.40	0.88/0.57	0.31	both
10.6/8.2	3.0	3.14	0.25	0.67/0.39	0.28	scaling
10.6/6.2	2.115	2.95	0.21	0.79/0.25	0.54	both
4.9/3.8	0.5	2.40	0.09	0.70/0.45	0.25	FF

KaonLT Experimental Details

- Hall C: k_e=3.8, 4.9, 6.4, 8.5, 10.6 GeV
- SHMS for kaon detection :
  - angles, 6 – 30 deg
  - momenta, 2.7 – 6.8 GeV/c
- HMS for electron detection :
  - angles, 10.7 – 31.7 deg
  - momenta, 0.86 – 5.1 GeV/c
- Particle identification:
  - Dedicated Aerogel Cherenkov detector for kaon/proton separation
    - Four refractive indices to cover the dynamic range required by experiments
  - Heavy gas Cherenkov detector for kaon/pion separation

THE CATHOLIC UNIVERSITY OF AMERICA



University of Regina

n	π_{thr} (GeV/c)	K_{thr} (GeV/c)	P_{thr} (GeV/c)
1.030	0.57	2.00	3.80
1.020	0.67	2.46	4.67
1.015	0.81	2.84	5.40
1.011	0.94	3.32	6.31

KaonLT Analysis Phases

*PionLT experiment running
See Dave Gaskell's talk!

1. Calibrations ✔
   - Calorimeter, aerogel, HG cer, HMS cer, DC, Quartz plan of hodo
   - Assure we are replaying to optimize our physics settings
2. Efficiencies and offsets* ← Current step
   - Luminosity, elastics, Heeps, etc.
3. First iteration of cross section ← On-deck
   - Extract the kaon electroproduction cross section
4. Fine tune
   - Fine tune values to minimize systematics
5. Repeat previous two steps
   - Repeat until acceptable cross sections are reached
   - This will highlight any potential complications
6. Possible attempt at form factor extraction
   - The Rosenbluth separation technique** is used to isolate the longitudinal term and thus the form factor can be extracted

**This is the first commissioning L-T separation for the HMS+SHMS setup

KaonLT Efficiencies and Offsets - Considerations

- This is perhaps the most important step in the entire analysis.
- These studies are so critical because of a $1/\Delta\epsilon$ amplification and possibly small $R=\sigma_L/\sigma_T$ in the systematic uncertainty of the σ_L

$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{\epsilon_1 - \epsilon_2}\frac{\Delta\sigma}{\sigma}\sqrt{(1/R+\epsilon_1)^2 + (1/R+\epsilon_2)^2}$$

- Careful analysis will allow the required precision cross section measurements for extracting form factors.
- Two main tools: luminosity scans and elastic analysis

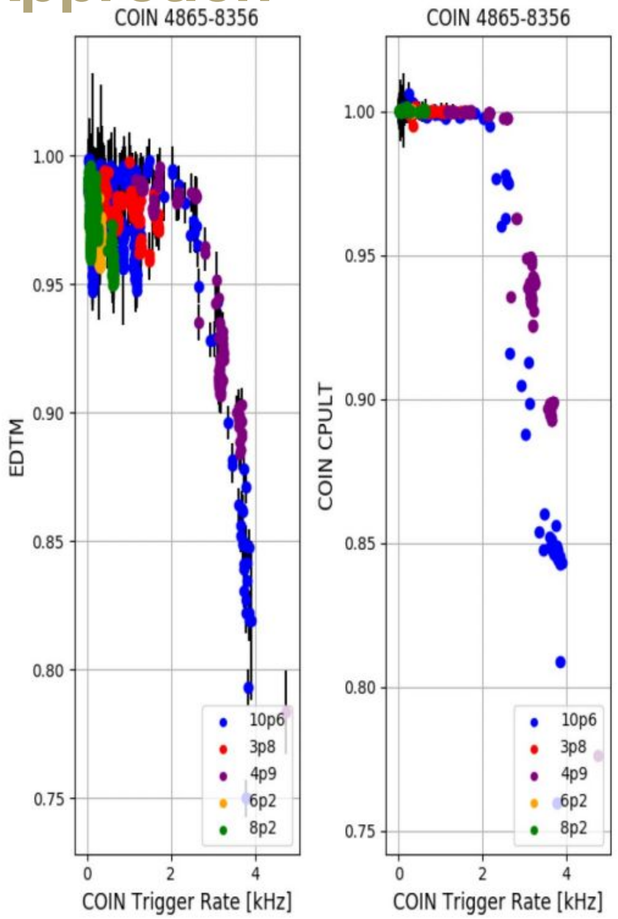
Source	pt-to-pt	t-correlated	scale (earlier)	scale (later)
Acceptance	0.4	0.4	2.0	1.0
PID		0.4	1.0	0.5
Coincidence Blocking		0.2		
Tracking efficiency	0.1	0.1	1.5	1.5
Charge		0.2	0.5	0.5
Target thickness		0.2	0.8	0.8
Kinematics	0.4	1.0		
Kaon Absorption		0.5	0.5	0.5
Kaon Decay		1.0	3.0	3.0
Radiative Corrections	0.1	0.4	2.0	2.0
Monte Carlo Model	0.2	1.0	0.5	0.5
Total	0.6	2.0	4.7	4.2

KaonLT Proposal, PAC 34

$$\text{Yield} = \frac{N}{Q_{tot}\epsilon_{tot}}$$

KaonLT Efficiencies - Experimental Approach

- Establishes the dead times and various efficiencies
- For KaonLT the luminosity scans provide a means to understand the accuracy of the efficiencies.
  - Data are taken as a function of current/rate on a carbon target and efficiency corrected yields are analyzed.
  - Since the carbon density should not change with current/rate
  - Any deviation of the yield from unity is indicative of an issue with the efficiencies that needs to be addressed.



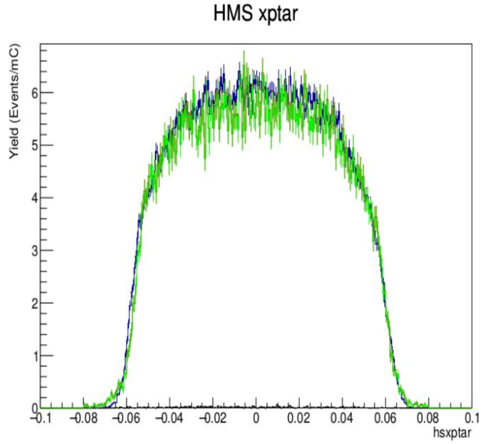
Studies by Ali Usman and Richard Trotta

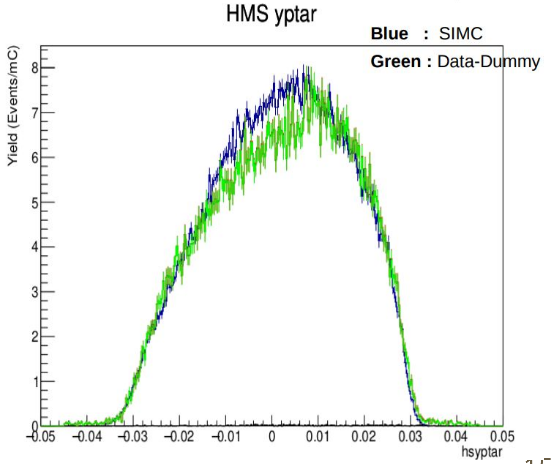
$$\text{Yield} = \frac{N}{Q_{tot}\epsilon_{tot}}$$

KaonLT Offsets - Experimental Approach

- Comprehensive understanding of the offsets to the kinematics and spectrometer acceptances.
- The elastic scans provide information on spectrometer offsets in angle and momentum
  - Elastic data is taken at the same or similar kinematics to those for the production data
  - The normalized yields are compared to those calculated with SIMC
  - Any deviations from unity are indicative of discrepancies in the spectrometer angle, momentum, or the beam energy used in the analysis
  - For instance, elastic singles data is used to fit angle and momentum offsets
    - The elastic coincidence data examines the deviation of invariant reconstructed mass, missing energy, and missing momentum from their nominal values.

Studies by Vijay Kumar





Extract the Kaon Electroproduction Cross Section

- SIMC, including a model of the experimental setup, is used to simulate a variety of effects.
- A model for the kaon electroproduction cross section is developed, including a $\chi 2$ minimization to achieve the best agreement between data and SIMC.
- This is achieved by iterating the model input cross section.
- The experimental cross section can then be extracted as long as the model input cross section properly describes the dependence on all kinematic variables.

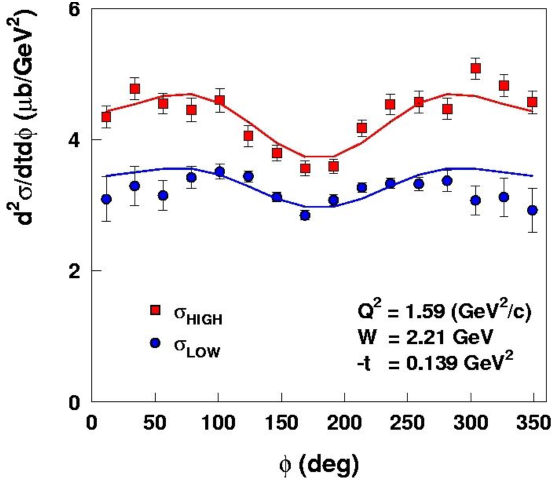
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Example polynomial showing expected kinematic dependency

$$\frac{d\sigma_i}{dt} = A_i \cdot e^{B_i|t-t_c|} \cdot \frac{1.0}{(1.0 + C_i Q^2)/(1.0 + C_i Q_c^2)}$$

L/T Separation

- σ_L is isolated using the Rosenbluth separation technique
- Measure the cross section at two beam energies and fixed W, Q^2, -t



*T. Horn et al., PhysRevC **97**(2006)192001*

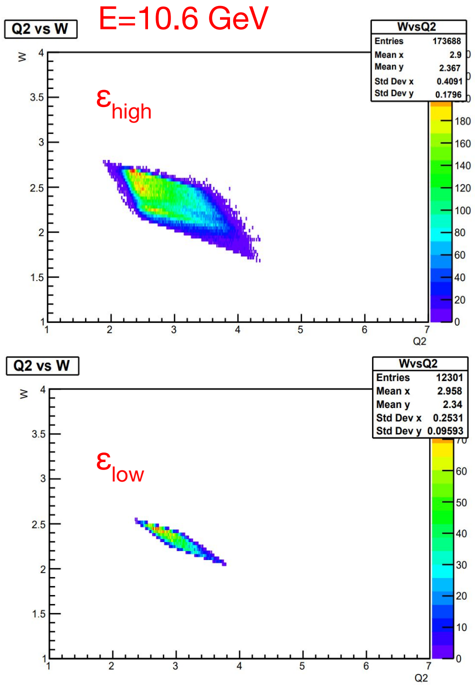
1. Phase space matching to constrain the kinematic region for the two differing beam energies
2. Extract cross section in -t and ϕ bins

$$\left(\frac{d\sigma^2_{exp}}{dtd\phi}\right)\Bigg|_{Q^2=\bar{Q^2},t=\bar{t}} = \frac{Y_{exp}}{Y_{SIMC}}\left(\frac{d\sigma^2_{model}}{dtd\phi}\right)\Bigg|_{Q^2=\bar{Q^2},t=\bar{t}}$$

3. This allows for the simultaneous extraction of the interference terms

$$2\pi\frac{d^2\sigma}{dtd\phi} = \varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos$$

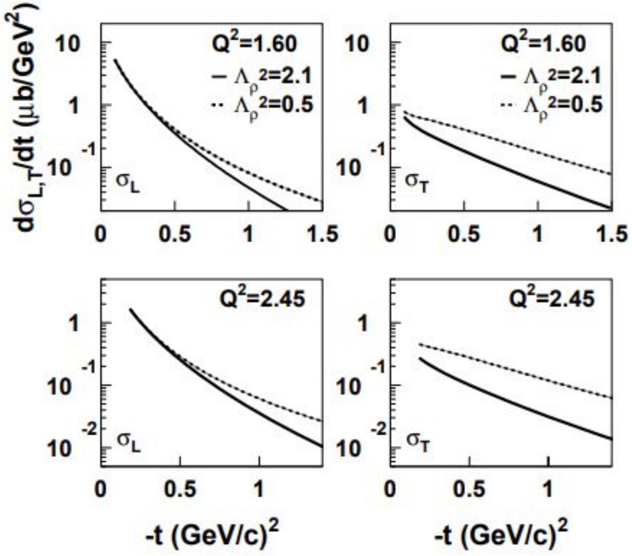
$$\frac{d\sigma}{dt} = \frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}$$



Form Factor Extraction

- The product of the kaon form factor is related to σ_L through the probability of the virtual photon interacting with a kaon
- If σ_L shows an exponential fall off with t this is a sign of the point-like behavior warranting the form factor extraction
- The extraction of the kaon form factor is done by fitting the longitudinal cross section calculated by the VGL Regge model to the experimental data.
- The model is evaluated for different values of Λ^2_{K+}

M. Vanderhaeghen, M. Guidal, and J.-M. Laget, Phys. Rev. C 57, 1454



T. Horn's Thesis

$$2\pi\frac{d^2\sigma}{dt\,d\phi} = \varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

$$\sigma_L \approx \frac{-tQ^2}{(t-m_K^2)^2} g^2_{KNN}(t) F_K^2(Q^2,t)$$

$$F_K(Q^2,t) = (1 + Q^2/\Lambda_K^2)^{-1}$$

$$\frac{\chi^2}{\text{dof}} = \frac{1}{\text{dof}} \sum_{\text{t bins}} \frac{(\sigma_L^{VGL} - \sigma_L^{exp})^2}{\Delta\sigma_L^2}$$

Summary and Outlook

- E12-09-011 ran Fall 2018, Spring 2019
  - Also have the PionLT data from Summer 2019, Fall 2021, and Winter 2022 available
  - See Dave Gaskell's PionLT talk!
- Currently in the late stages of the second phase of analysis
  - PhD students analyzing data: Ali Usman, Vijay Kumar, and Richard Trotta
- Next stage is to extract the kaon electroproduction cross section for both Λ, Σ^0 channels
  - This is achieved by iterating the model input cross section.
  - The experimental cross section can then be extracted as long as the model input cross section properly describes the dependence on all kinematic variables.

Thanks to everyone in the KaonLT collaboration

Salina Ali, Ryan Ambrose, Darko Androic, Whitney Armstrong, Carlos Ayerbe Gayoso, Samip Basnet, Vladimir Berdnikov, Hem Bhatt, Deepak Bhetuwal, Debaditya Biswa, Peter Bosted, Ed Brash, Alexandre Camsonne, Jian-Ping Chen, Junhao Chen, Mingyu Chen, Michael Christy, Silviu Covrig, Wouter Deconinck, Markus Diefenthaler, Burcu Duran, Dipangkar Dutta, Mostafa Elaasar, Rolf Ent, Howard Fenker, Eric Fuchey, Dave Gaskell, David Hamilton, Ole Hansen, Florian Hauenstein, Nathan Heinrich, Tanja Horn, Garth Huber, Shuo Jia, Mark Jones, Sylvester Joosten, Muhammad Junaid, Md Latiful Kabir, Stephen Kay, Vijay Kumar, Nathaniel Lashley-Colthirst, Bill Li, Dave Mack, Simona Malace, Pete Markowitz, Mike McCaughan, Robert Michaels, Rachel Montgomery, Jacob Murphy, Gabriel Niculescu, Maria Niculescu, Zisis Papandreou, Sanghwa Park, Eric Pooser, Love Preet, Julie Roche, Greg Smith, Petr Stepanov, Holly Szumila-Vance, Vardan Tadevosyan, Aram Teymurazyan, Richard Trotta, Hakob Voskanyan, Carlos Yero, Ali Usman

(Proposal to Jefferson Lab PAC 34)

Studies of the L-T Separated Kaon Electroproduction Cross Section from 5-11 GeV

December 15, 2008

Extra Slides

SHMS small angle operation

- Some issues with opening and small angle settings at beginning of run
  - SHMS at 6.01°
  - HMS at 12.7°

[12/17/18]